Development and operation of an electro-optical simulator as part of the space mission eLISA

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GPhys 06/07/15

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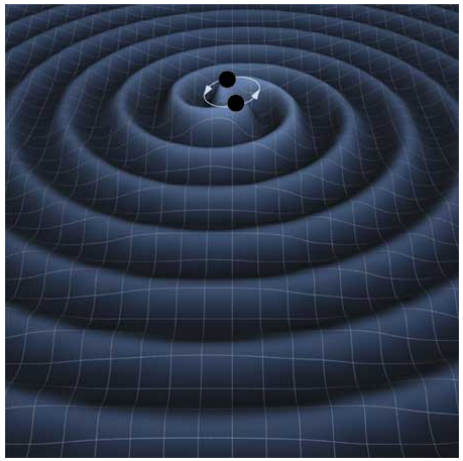
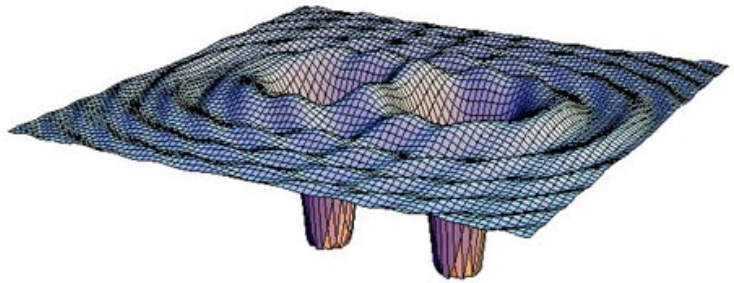
Introduction to gravitational waves

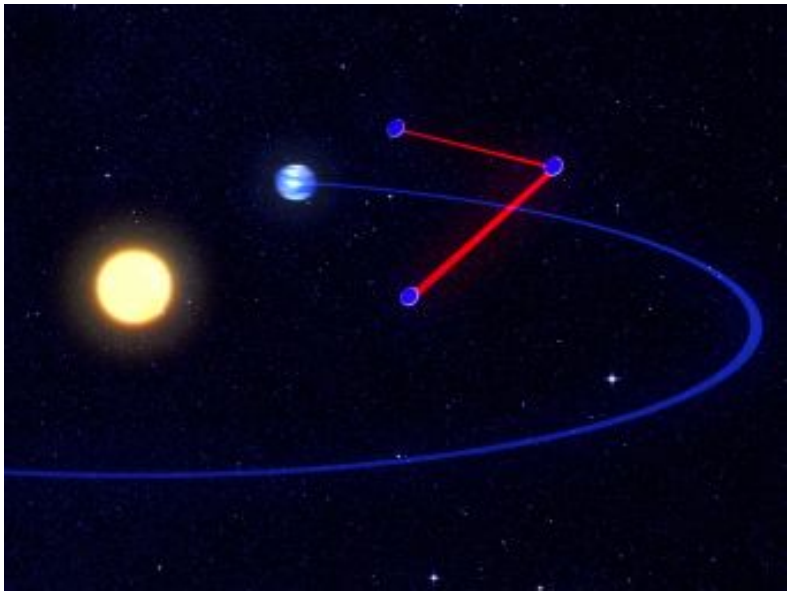


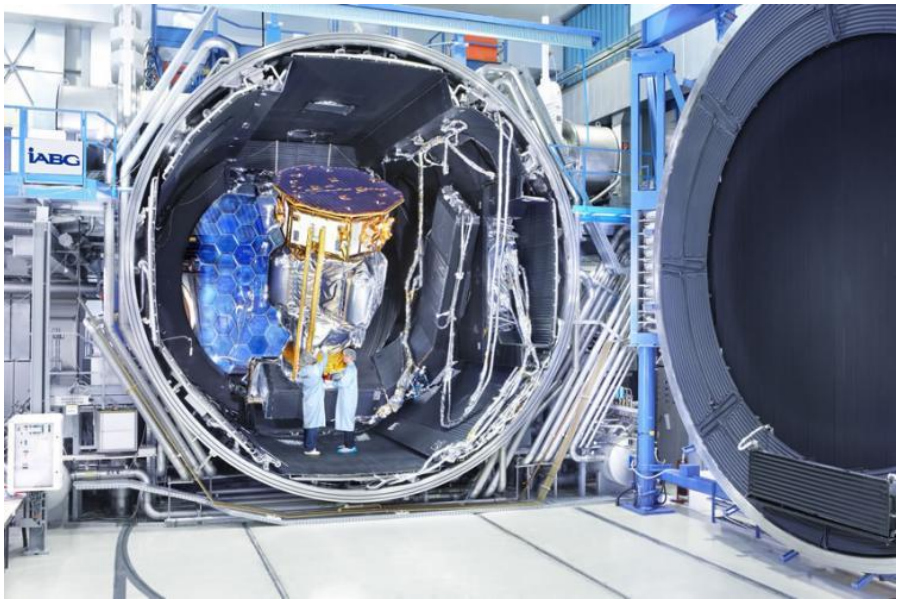


- Propagating perturbation of the space-time metric
- Main sources are binary systems of black holes, neutron stars, white dwarfs and primordial gravitational waves
- Predicted in 1918 by Einstein
- Never directly detected ... but undirectly observed by R. Hulse and J. Taylor by observations of the binary pulsar PSR B1913+16
- Direct observation very difficult : $\Delta L/L = 10^{-21}$ (1 pm for 1 Mkm)

Plan

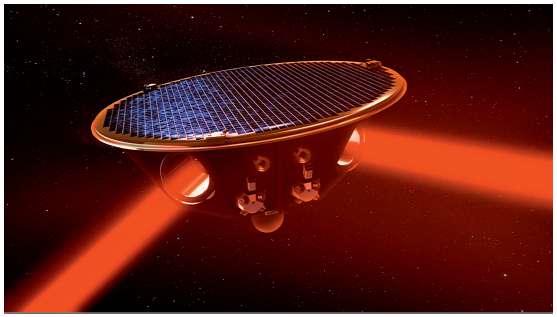
A space based detector : eLISA (evolved Laser Interferometer Space Antenna





- from LISA to eLISA : redefining the mission
- Gravitational universe theme selected by ESA for L3 with estimated launch in 2034
- launch of LISA Pathfinder in september/october 2015

A space based detector : eLISA (evolved Laser Interferometer Space Antenna



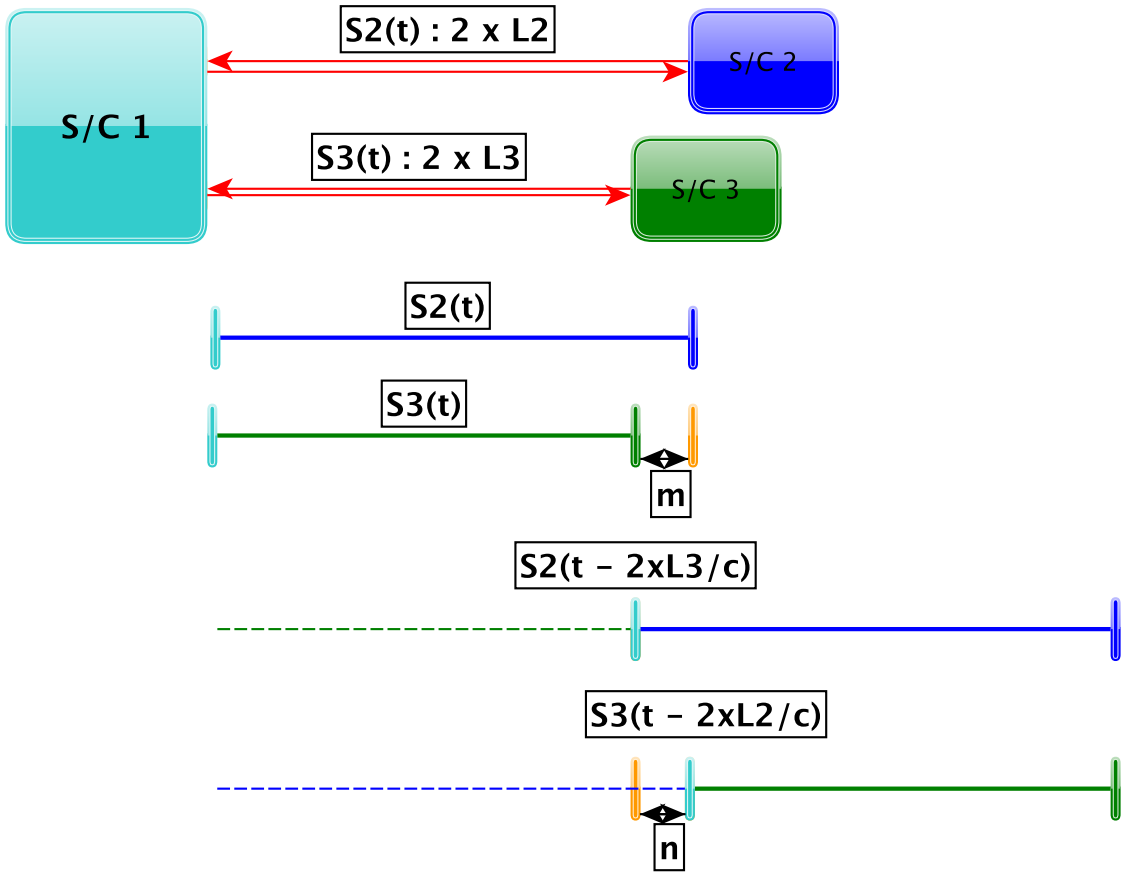
- 3 satellites, 2 arms forming a giant heterodyne interferometer
- 1 million km arms allowing to be sensitive to variations of picometer order induced by gravitational waves
- Working principle :
  - beat note is created between distant and local arm
  - phasemeter measures phase $\Delta\phi(t)$ of beat note and reference
  - when a GW passes through the detector -> distance variation -> phase variation

A space based detector : eLISA (evolved Laser Interferometer Space Antenna

The goal of eLISA is to detect deformations as small as $\Delta L/L \approx 10^{-21}$ (i.e 10 pm per million of km) around 5 mHz requiring a perfect knowing of noise sources such as :

- laser noise
- clock noise
- optical path lenght variation due to thermodynamical effects
- radiative pressure from the sun
- cosmic rays charging the test masses
- acceleration of the test masses and optical bench
- uncertainty on the laser pointing
- noise due to diffuse light in the optical bench
- shot noise
- and many other effects ...

TDI : Time Delay Interferometry

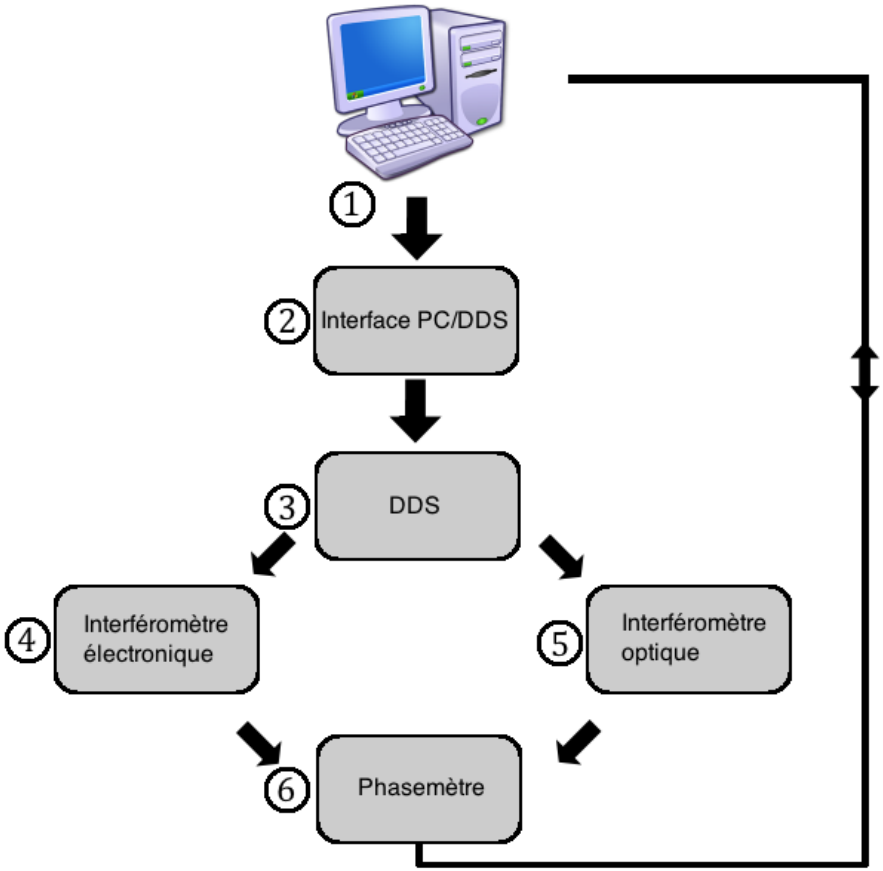


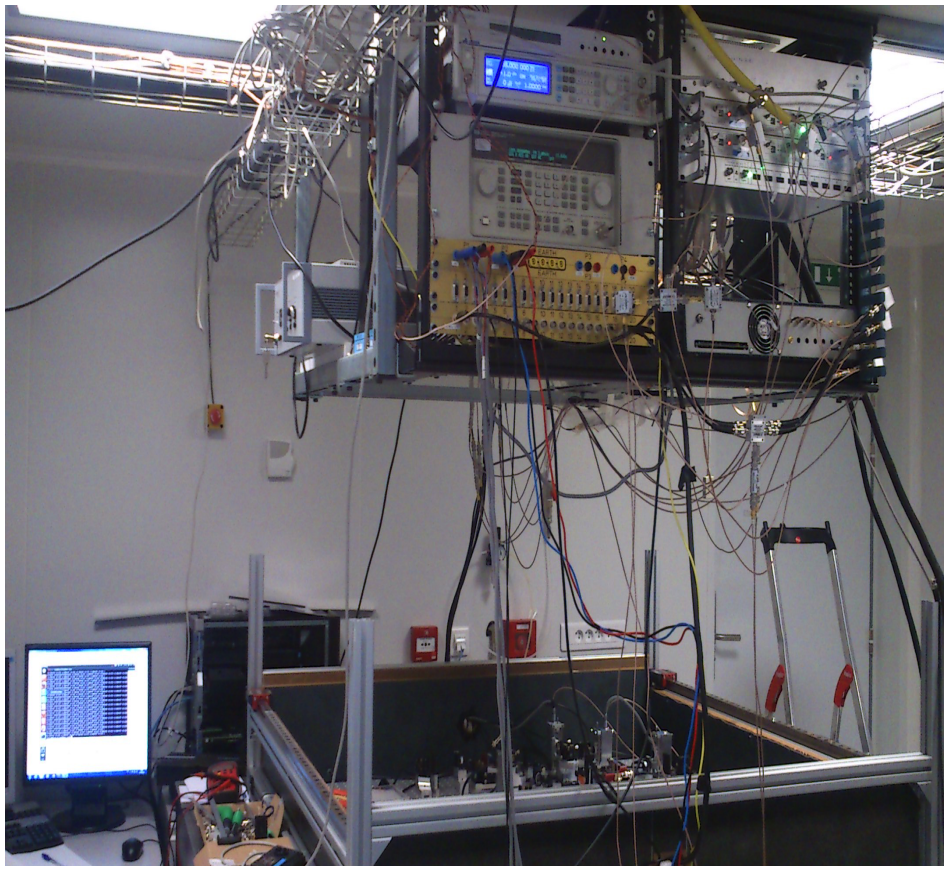
$$S_{TDI} = [S_2(t) - S_3(t)] - \left[S_2(t - \frac{2L_3}{c}) - S_3(t - \frac{2L_2}{c})\right]$$

$$= m - n = 0$$

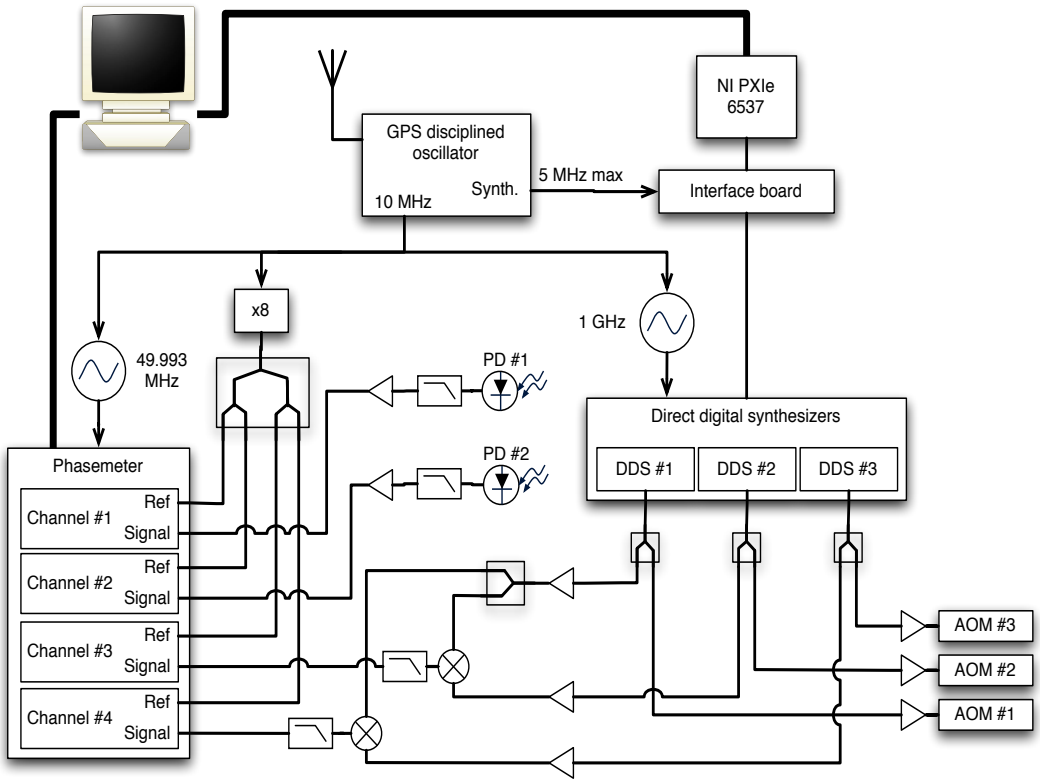
Plan

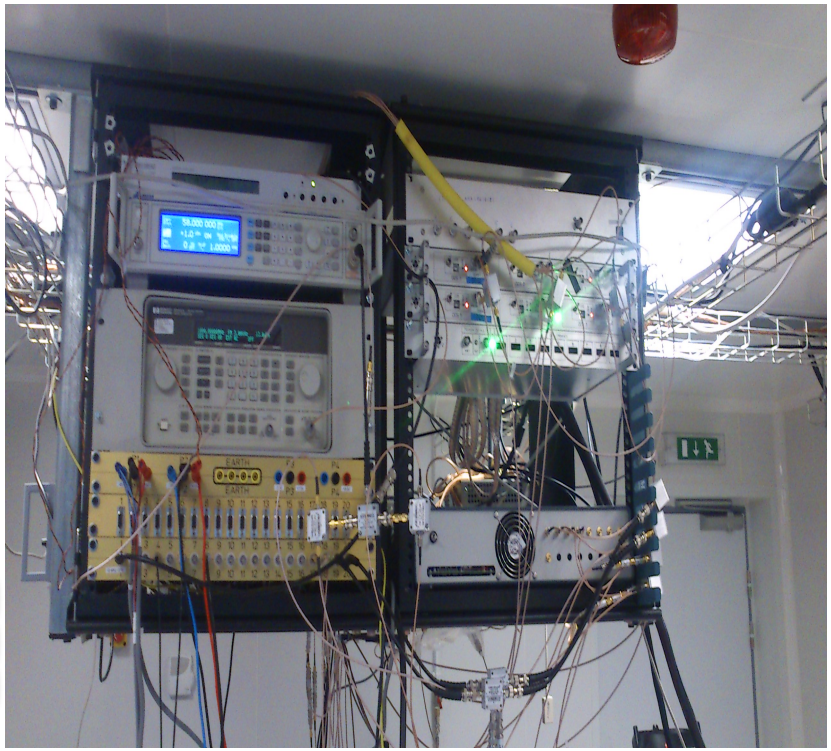
LOT : Lisa On Table, an electro-optical simulator of eLISA - Overview





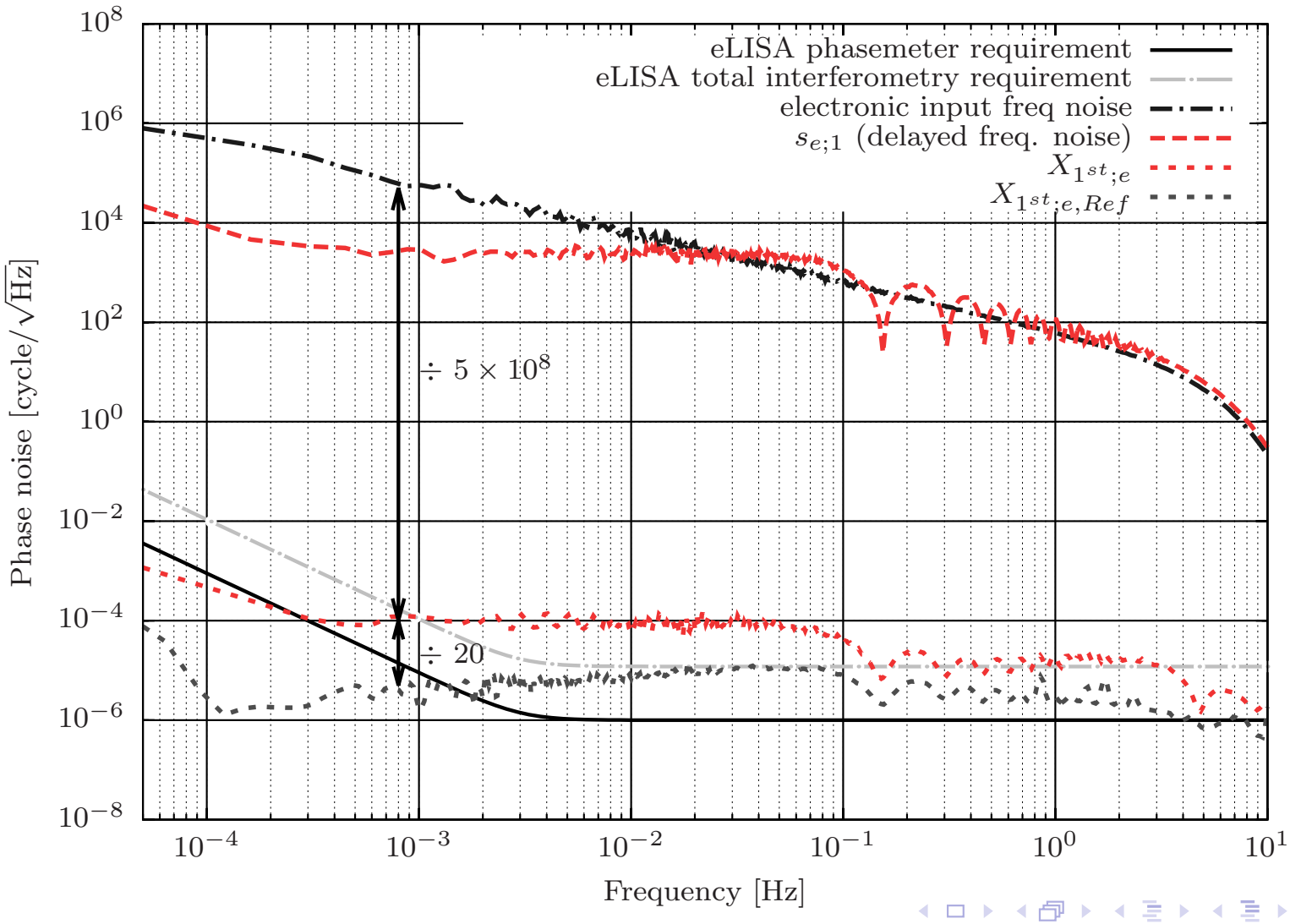
LOT : Lisa On Table, an electro-optical simulator of eLISA - Electric interferometer



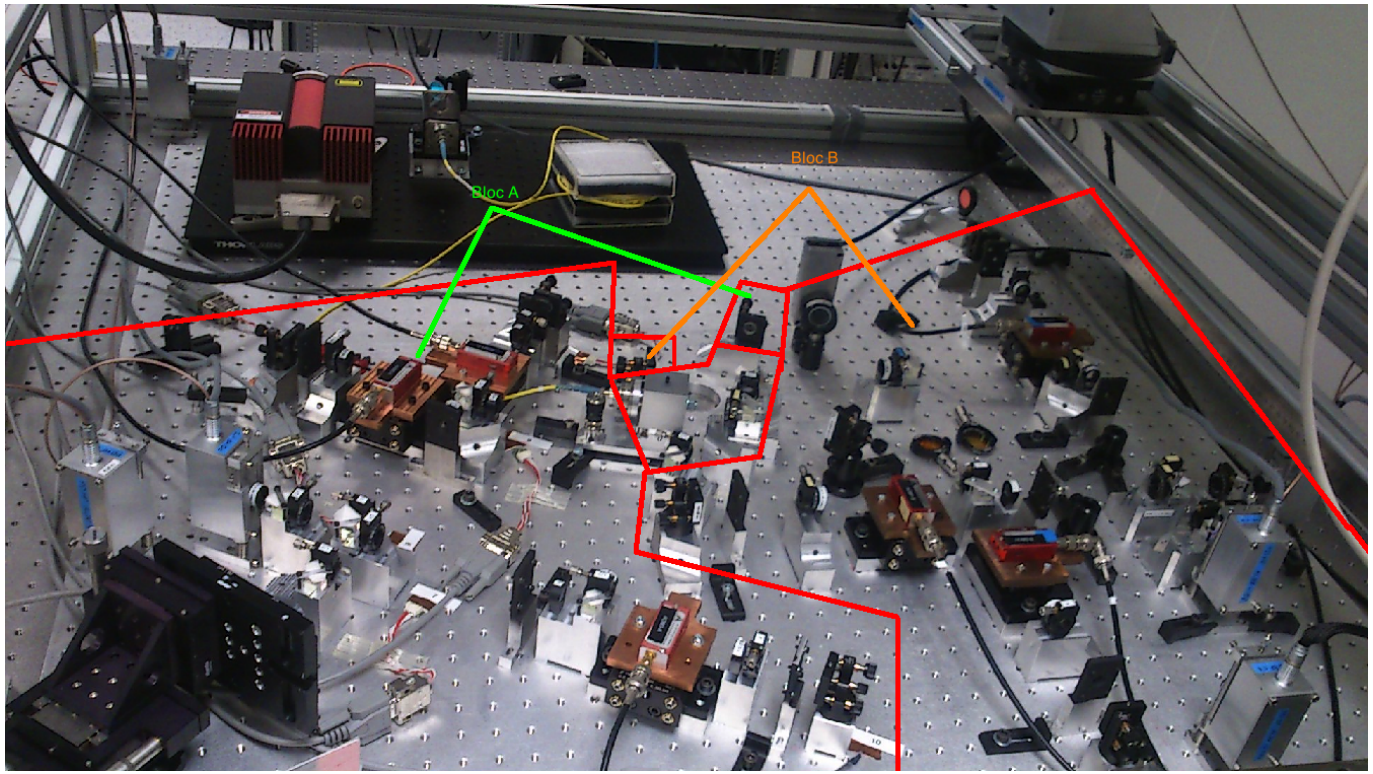


- One part of DDS signals is sent to AOMs (optical part)
- Another part is electronically mixed and low-pass filtered

LOT : Lisa On Table, an electro-optical simulator of eLISA - Electric TDI noise cancellation

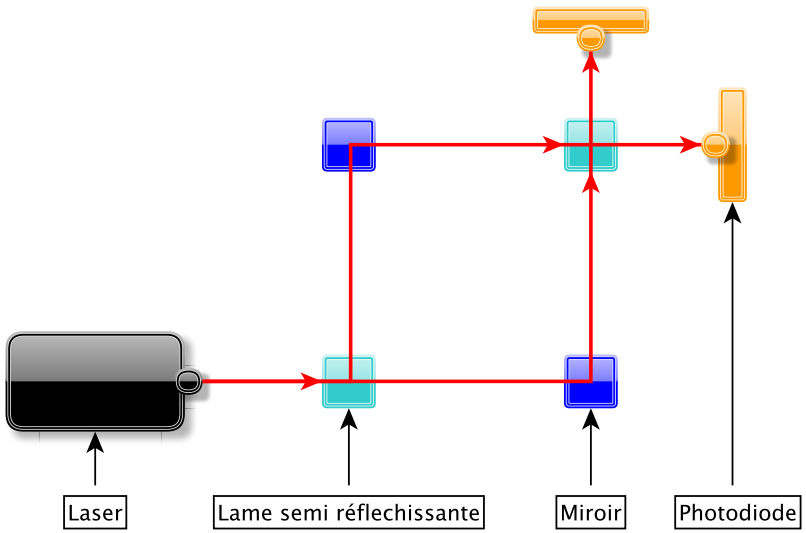


LOT : Lisa On Table, an electro-optical simulator of eLISA - Optical interferometer

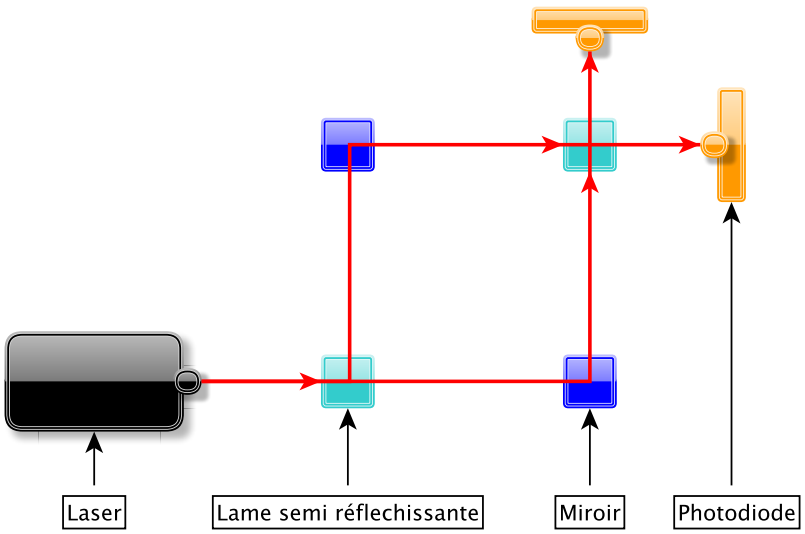


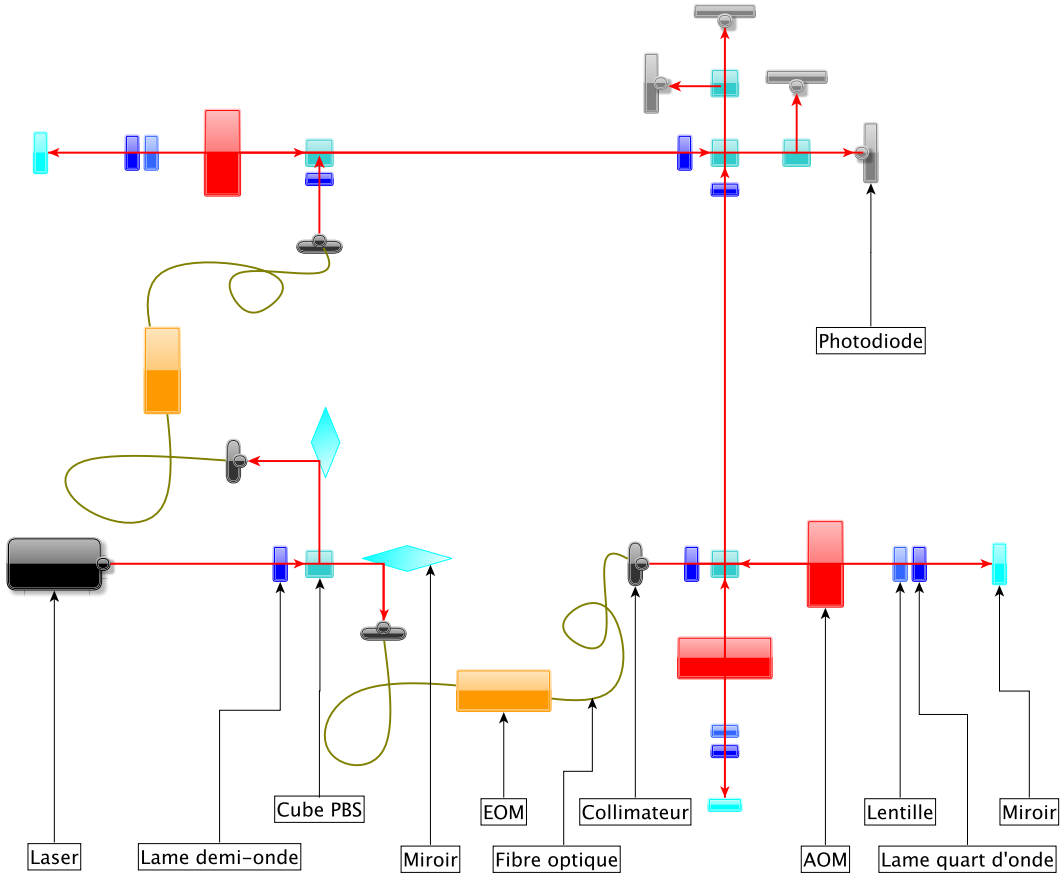
- a heterodyne Mach-Zehnder interferometer
- 2 blocs each one representing a satellite and 3 arms
- each arm simulated by an association of lense, polarizing plate, mirror and acousto-optical modulator

LOT : Lisa On Table, an electro-optical simulator of eLISA - A modified Mach-Zehnder interferometer

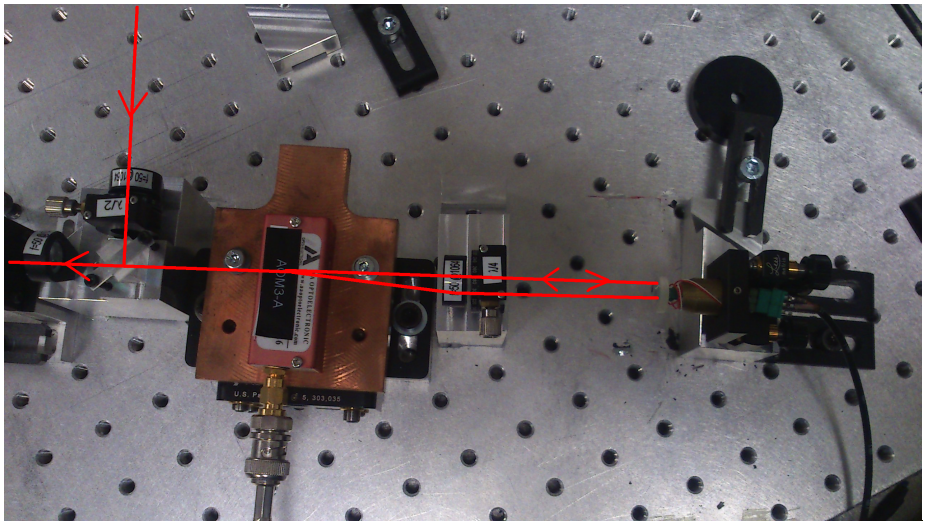


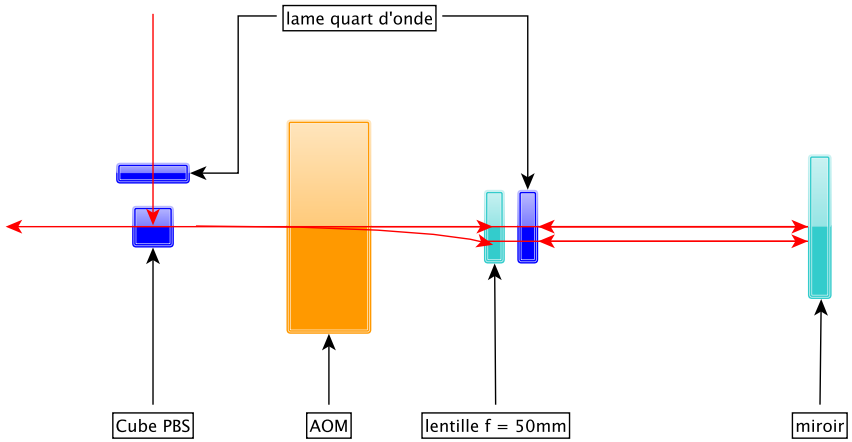
LOT : Lisa On Table, an electro-optical simulator of eLISA - One eLISA arm





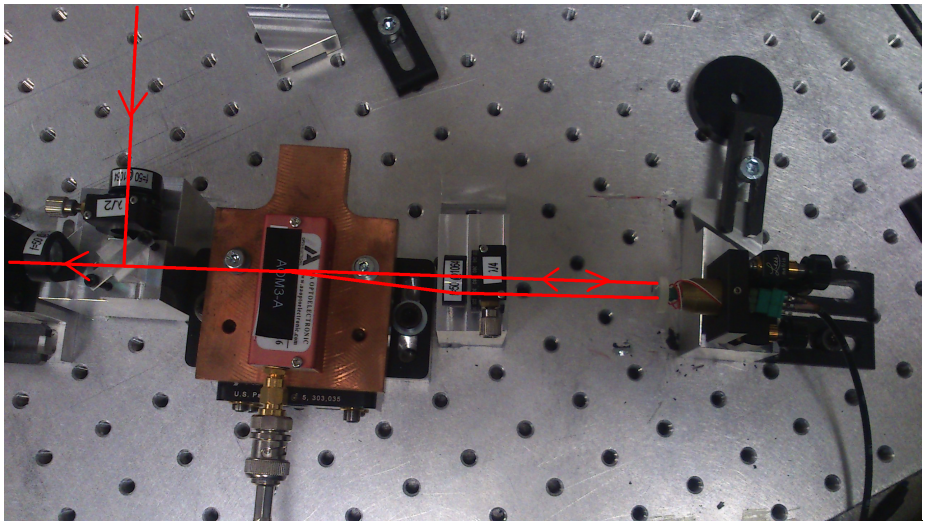
LOT : Lisa On Table, an electro-optical simulator of eLISA - One eLISA arm

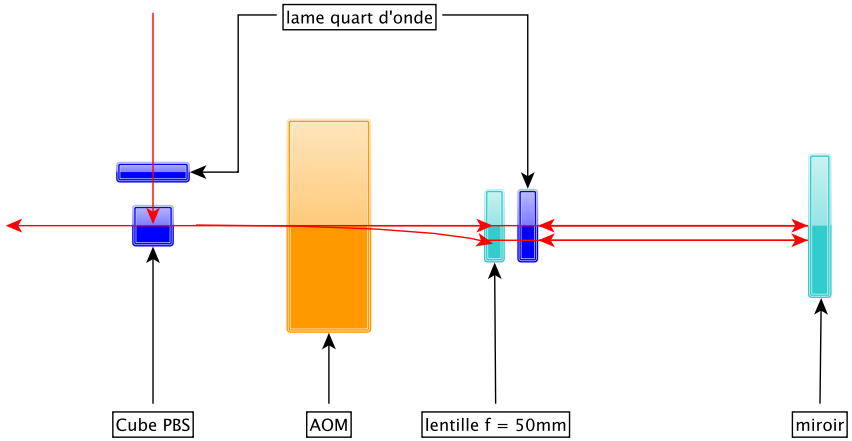


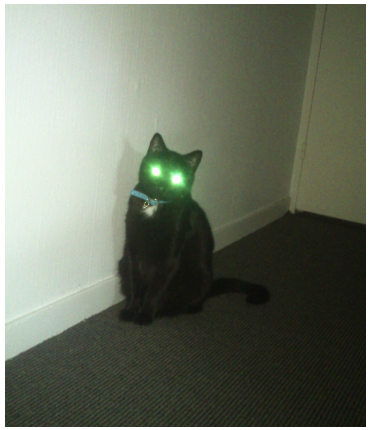


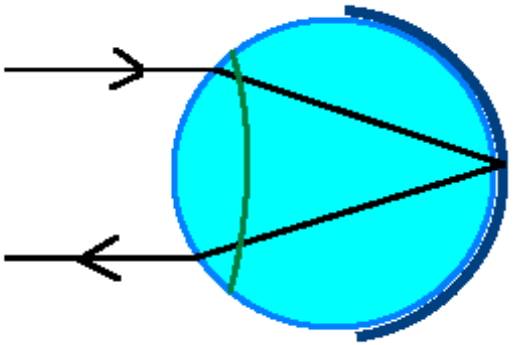
- laser is deflected and shifted in frequency two times
- deflection angle is not constant and varies with frequency
- cat eye configuration keeps alignment even if angle is changing

LOT : Lisa On Table, an electro-optical simulator of eLISA - Opical TDI noise cancellation

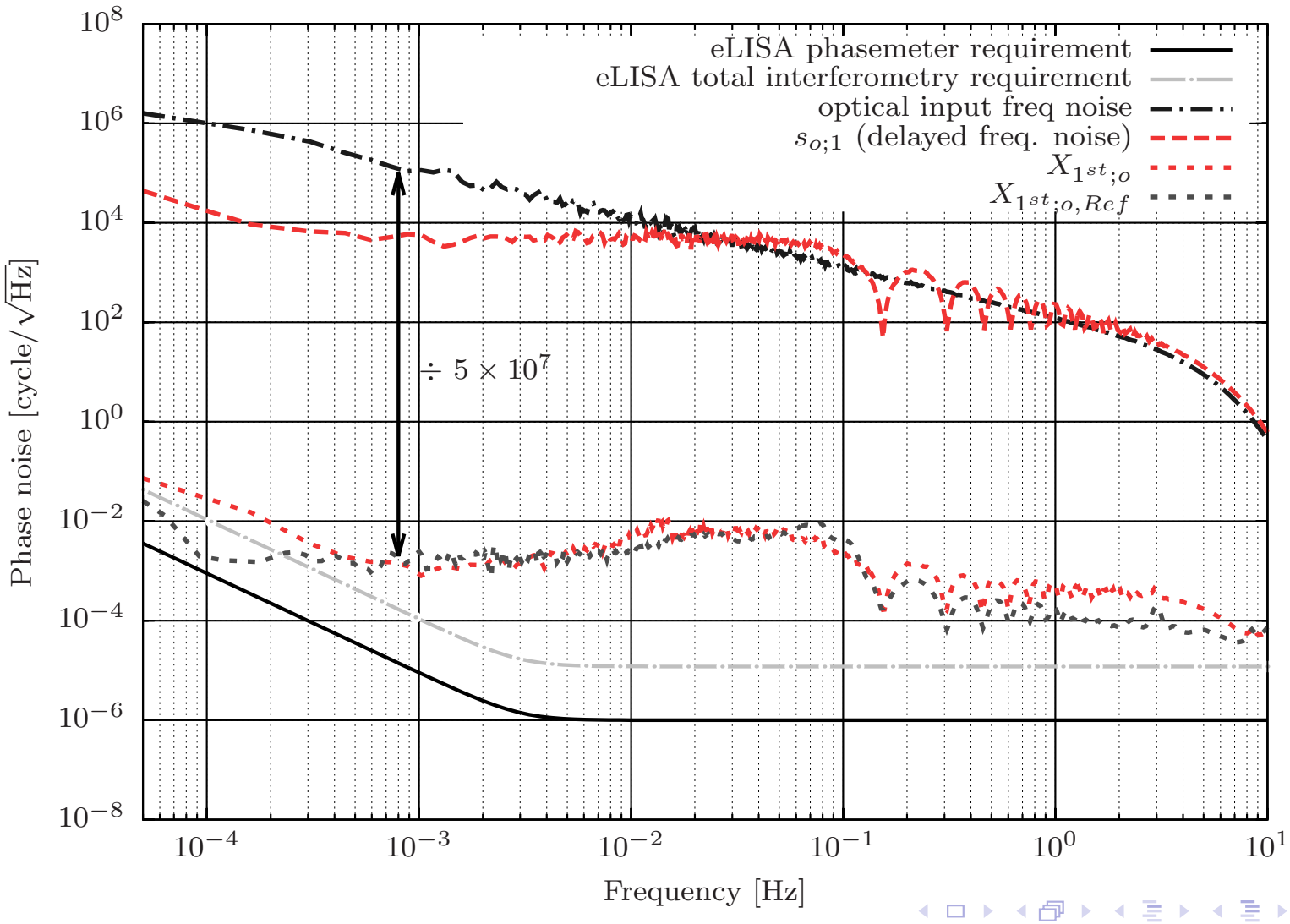








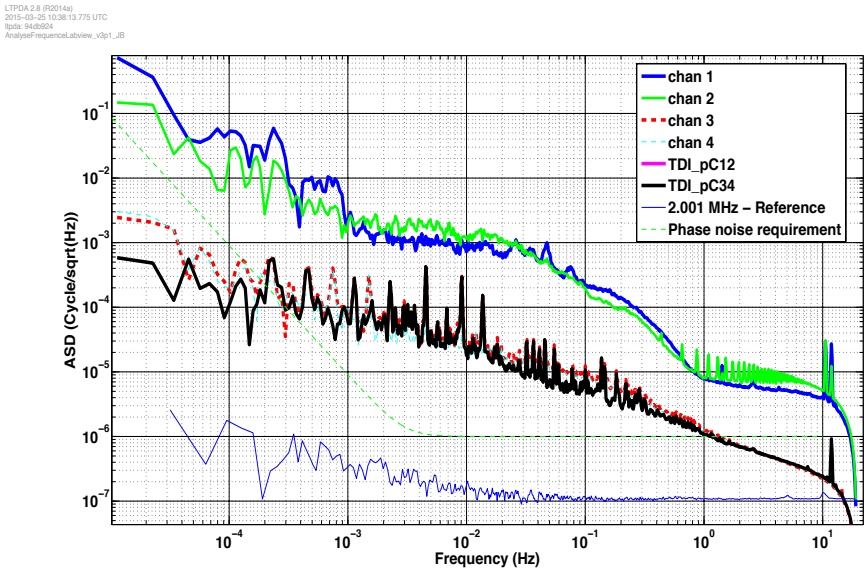
LOT : Lisa On Table, an electro-optical simulator of eLISA - Opical TDI noise cancellation

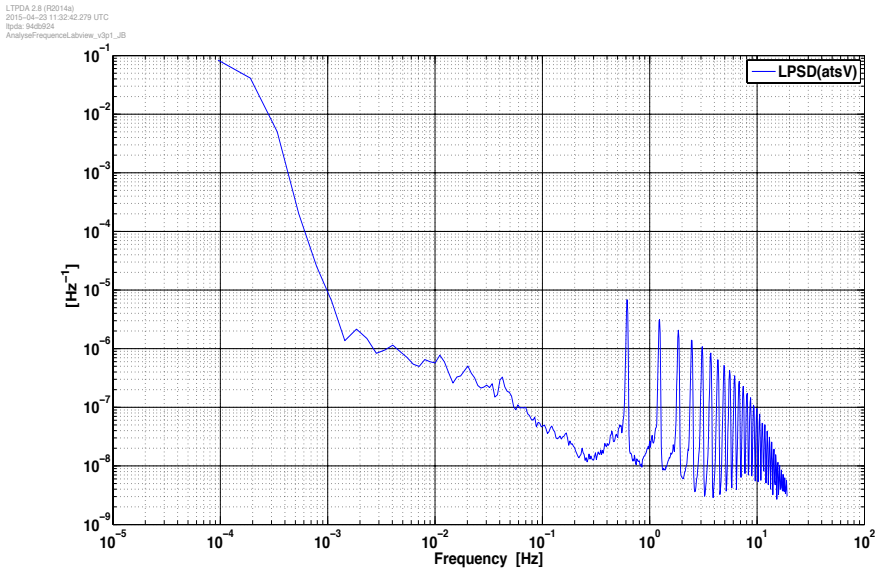


Improvement of the experiment

- thermal insulation of the optical bench
- use of air cushion
- piezo oscillators on the mirror for active correction of the optical path lenght
- heat device to reduce turbulences by creating temperature layers
- ongoing work :
  - stabilization of laser power
  - implementation of electro-optical modulators to simulate clock noise corrections
  - replacement of the NI device by a FPGA card
  - adding possibility to simulate realistic variable delays and frequency shifts due to orbitography and doppler effect
  - transfer into a vacuum chamber

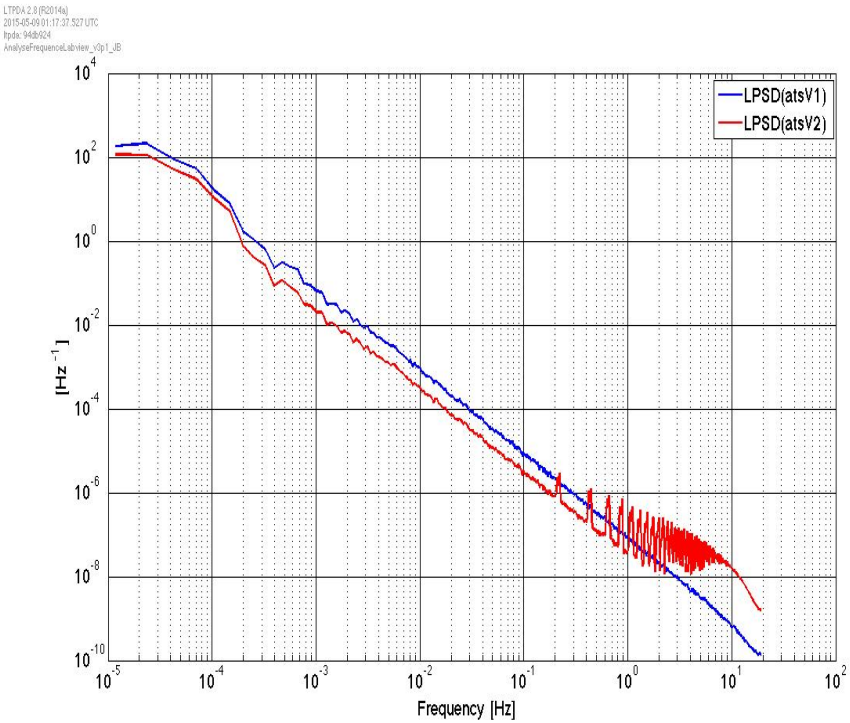
Improvement of the experiment - Active compensation of optical path length

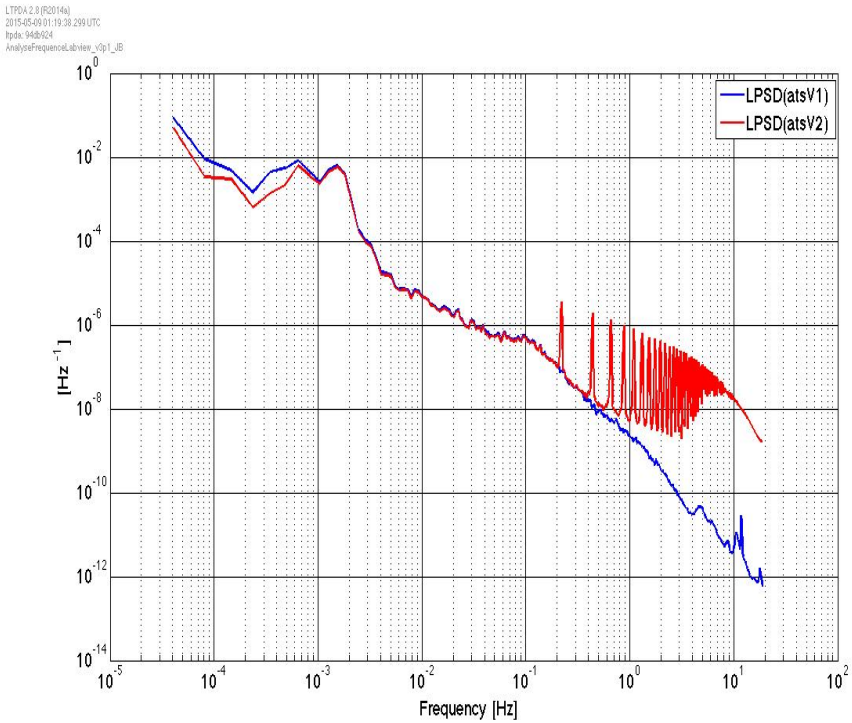




- with optical path length compensation the optical noise is reduced by at least 1 order of magnitude
- presence of unexplained peaks on the 2nd channel
- Investigations excluded all active components : control electronic, AOM, piezo oscillator, photodiodes and phasemeter

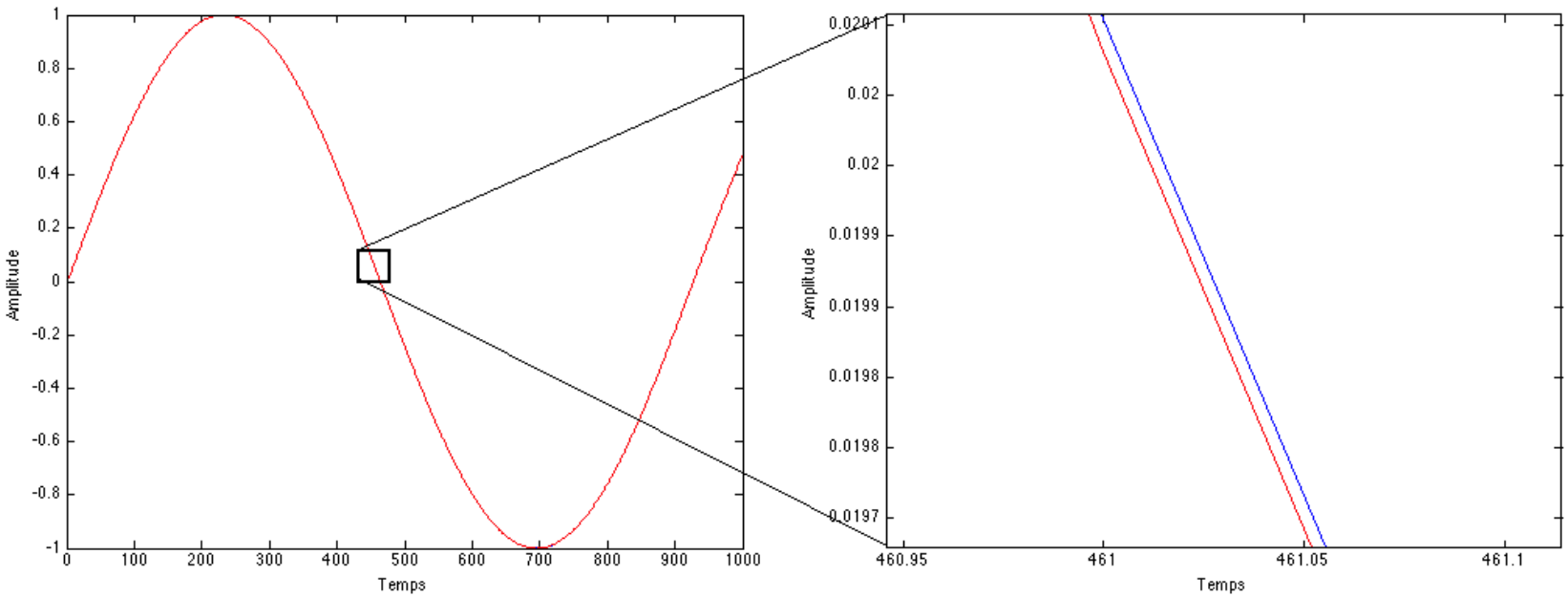
LOT : Lisa On Table, an electro-optical simulator of eLISA, optical part





Difference between power compensation off (left) and on (right)

LOT modelisation



2 main topics regarding the modelization :

- modelisation of quantization effects (amplitude and phase) of DDS + z transform phasemeter model
- modelisation of optical signals considering all modulations (piezo, EOM and AOM), calcul of all involved beat notes and Bessel decomposition of the 3 important components (piezo, Δf_{AOM} and Δf_{EOM})

Plan

Conclusion

- Hardware simulator taking into account many aspects of eLISA
- TDI tests successfull
- More realistic tests including Doppler effect ongoing
- Improvements to reduce intrinsic noise are underway :
  Active compensation of optical pathlength, compensation of laser power fluctuations, FPGA card to bypass NI system
- Forthcoming eLISA like developments :
  Clock synchronization scheme with EOMs, time variable delays and frequency shifts based on realistic orbithography, arm-locking

"Status of the eLISA on table (LOT) electro-optical simulator for space based, long arms interferometers"
P. Gruning et al. - Experimental Astronomy - March 2015

Thank you !